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ADP010583 thru ADP010608

Impact of Aircraft Emissions on the Global Atmosphere

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1. Introduction

Aviation is a very fast growing economic sector. For instance, in 1998 the number of passengers travelling with Deutsche Lufthansa grew by 9% relative to the previous year. Globally the annual increase rate in air transportation is more than 5%. The rapidly increasing demand for air transport outpaces technological improvements in aircraft and improvements in air traffic management systems: the mean annual increase rate of fuel burn was 2.2% for the years 1985 to 1995. Similar increase rates are expected for the future.

Aircraft emit gases (CO_2, H_2O, NO_x SO_2, UHC, etc.), aerosols (e.g., soot) and aerosol precursors (e.g., SO_3, H_2SO_4). Hence, aircraft modify the composition of the atmosphere either directly due to these emissions or indirectly via chemical processes, e.g., NO_x modifies the ozone concentration. The main concern related with these emissions is the potential for climate change by perturbing the Earth's radiative budget as a result of several processes: (1) the emission of radiatively active substances (e.g. CO_2 or H_2O); (2) the emission of chemical species which produce or destroy radiatively active substances (like NO_x, which modifies the O_3 concentration, or SO_2, which oxidizes to sulfate aerosols); (3) the emission of substances (e.g. H_2O, soot) which trigger the generation of additional clouds (e.g. contrails).

Due to the internal variability of the atmosphere, it is extremely difficult to detect the climatic impact of a single economic sector in climate observations or in simulations with comprehensive climate models. Therefore we consider the radiative forcing[2] (RF) associated with various perturbations of the atmospheric composition. RF is known to be a good predictor of global climate change in terms of variables like the global mean surface temperature change or mean sea level rise. On average the global mean surface temperature increases by 0.6 K per 1 Wm^{-2} of RF.

In the following we consider various individual contributions to the radiative forcing and concentrate on 1992 and 2050. While the current and past emissions of aviation are reasonably well known, we have no reliable forecasts of the future. Hence, we make use of emission scenarios, which have been developed for various economic and technological assumptions. We study in greater detail the aviation scenario Fa1 that makes similar economic assumptions as the IPCC scenario IS92a for all anthropogenic emissions. In the latter scenario the CO_2 concentration increases by 0.6% annually. The aviation scenario Fa1 assumes a mean annual increase rate of 1.7% for the fuel burn until 2050.

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[2] Radiative forcing is the change of the net radiative flux at the tropopause, which instantaneously occurs after a perturbation of the atmospheric composition. Apart from a radiative adjustment of the stratosphere no changes are allowed to occur in the atmosphere before calculating RF.

Paper presented at the RTO SAS Symposium on "Approaches to the Implementation of Environment Pollution Prevention Technologies at Military Bases", held in Budapest, Hungary, 5-7 May 1999, and published in RTO MP-39.

2. Components to radiative forcing due to aviation

CO_2

The atmospheric life time (adjustment time) of CO_2 is in the order of decades to centuries. Hence, CO_2 is well-mixed within the atmosphere, and the location of the emission is not important. In 1992, about 1.2 ppmv of the atmospheric CO_2 was caused by air traffic. This is 1.6% of all anthropogenic increase (76 ppmv) since 1800. According to scenario Fa1 the aircraft contribution will increase to 6.3 ppmv until 2050 (2.9% of all anthropogenic CO_2 according to scenario IS92a). The corresponding aviation RFs are 0.018 and 0.074 Wm^{-2} for 1992 and 2050, respectively (Figure 1). For comparison, all anthropogenic CO_2 caused RFs of 1.5 and 3.8 Wm^{-2}, respectively.

O_3

The 1992 NO_x emissions of the subsonic air traffic lead to a calculated regional increase of the O_3 concentration of 3% relative to the unperturbed background (without aircraft) due to smog reactions. Following scenario Fa1, this value will double until 2050. Ozone is radiatively active in both, the solar and terrestrial ranges of the spectrum. The aircraft-induced ozone perturbations result in positive RFs of 0.023 and 0.06 Wm^{-2} for 1992 and 2050, respectively (Figure 1). The RF exhibits a strong latitudinal dependence: on the northern hemisphere it is about one order of magnitude larger than on the southern hemisphere.

CH_4

The NO_x emissions also increase the sinks for atmospheric methane (CH_4). Hence aviation results in a reduction of the anthropogenic increase of CH_4 (e.g., from rice fields). Therefore the net effect of aircraft is a negative RF due to the CH_4 changes: -0.014 Wm^{-2} in 1992 and -0.045 Wm^{-2} in 2050. However, as the atmospheric life time of CH_4 is in the range of a decade, CH_4 becomes well-mixed. Therefore the aviation methane effects cannot compensate for the aircraft ozone effects due the different regional patterns of RF.

H_2O

Despite the fact that H_2O is one of the main emission products of aircraft engines, aviation H_2O cannot significantly disturb the background concentration of H_2O as it is effectively removed from the atmosphere by precipitation. Therefore the direct climate effect of water vapour from aviation is minor.[3]

Contrails

Water vapour emissions from aircraft trigger the generation of contrails (condensation trails) which can persist for tens of minutes to several hours for suitable background conditions. Due to the 1992 air traffic 0.1% of the Earth was covered by persistent contrails. In regions with heavy air traffic the computed coverage was larger: 1.1% over Europe and 1.4% over the USA. The global mean radiative forcing was 0.02 Wm^{-2}. The contrail coverage will grow more rapidly than fuel burn as modern, more efficient aircraft release a cooler exhaust for the same amount of fuel burnt than older aircraft do, and as relatively more fuel will be burnt at cruising altitude than at lower atmospheric levels. According to scenario Fa1 the global mean coverage by persistent contrails will increase to 0.5% until 2050 with a RF of 0.1 Wm^{-2}.

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[3] The situation is totally different for a projected large fleet of supersonic aircraft: for this scenario the water vapour effect is dominant.

Aerosols

Both, sulphate and black carbon (soot) aerosols only have a very small direct radiative effect on climate.

Clouds

Aerosols from aviation may accumulate in the atmosphere and may have a significant impact on the "natural" cirrus cloudiness. However, apart from single cases where aircraft aerosols caused measurable changes of cirrus particle properties, we do not know enough yet in order to quantify the indirect effect of aircraft on clouds. Some very preliminary estimates of RF due to changes in cirrus cloud cover range from 0 to 0.04 Wm^{-2} for the 1992 climate.

3. The summed aircraft effects

Figure 1 compares the various contributions of aircraft-induced RF for 1992 and for scenario Fa1 in 2050. Obviously, the contributions due to CO_2, O_3 and contrails are of similar magnitude. The CH_4 contribution also has a similar value, but is of opposite sign. All other contributions are at least one order of magnitude smaller.

In 1992 the total aviation RF (including contrails, but without other cloud changes) was +0.05 Wm^{-2}. This is 3.5% of the 1.4 Wm^{-2} for all anthropogenic activities. According to scenario Fa1 the aviation RF will increase to +0.19 Wm^{-2} until 2050 (5.1% of the 3.8 Wm^{-2} expected for all anthropogenic emissions under scenario IS92a). Other aviation scenarios result in an aviation contribution of about 10%.

Further details will be available from the forthcoming IPCC Special Report "Aviation and the Global Atmosphere".[4]

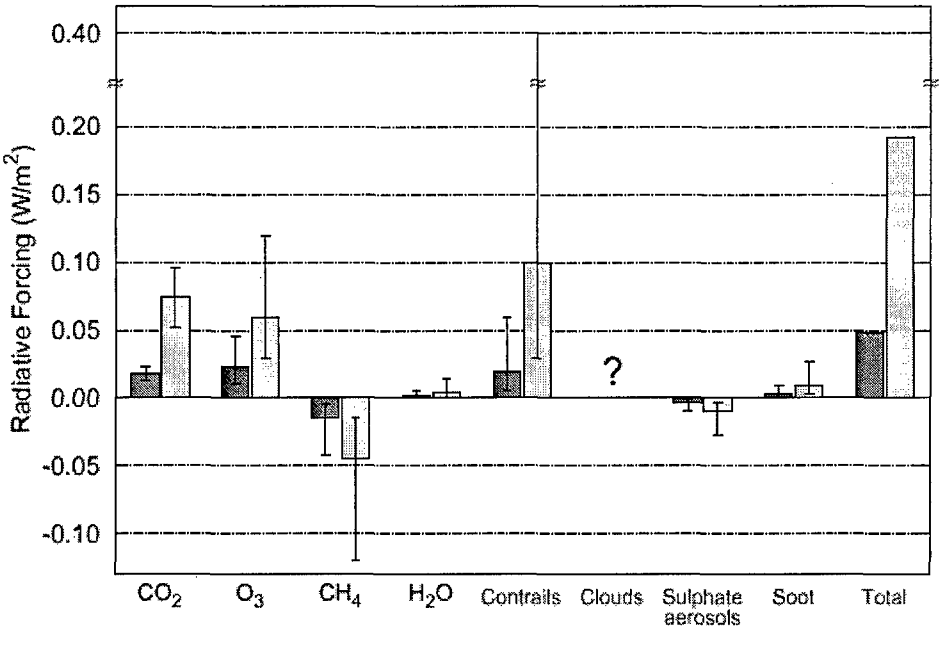

Figure 1: Components of radiative forcing due to aircraft for 1992 and for 2050 (according to scenario Fa1).

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[4] This IPCC report will be published by Cambridge University Press in summer 1999.

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Impact of Aircraft Emissions on the Global Atmosphere

Information from the IPCC Special Report „Aviation and the Global Atmosphere"

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Joint RTA/SAS Panel and CCMS Symposium
Approaches to the Implemantation of
Environmental Pollution Prevention Technologies at Military Bases
Budapest, 5-7- May 1999

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Aviation and the Global Atmosphere - Contents (1)

Summary for Policymakers
Lister, Penner, Griggs, Houghton + 30 further LAs

1. Introduction
Ellis, Harris, Lister, Penner

2. Impacts of Aircraft Emissions on Atmospheric Ozone
CLAs: Derwent (UK), Friedl (USA); 6 LAs, 45 Cs

3. Aviaition-Produced Aerosols and Clouiness
CLAs: Fahey (USA), Schumann (Germany); 8 LAs, 21 Cs

CLA = Coordinationg Lead Author
LA = Lead Author
C = Contributor

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Aviation and the Global Atmosphere - Contents (2)

4. Modeling the Chemical Composition of the Future Atmosphere
   CLAs: Isaksen (Norway), Jackmann (USA); 9 LAs, 19 Cs

5. Solar Ultraviolet Irradiance at the Ground
   CLAs: Ryan (Australia), Frederick (USA); 3 LAs, 2 Cs

6. Potential Climate Change from Aviation
   CLAs: Prather (USA), Sausen (Germany); 4 LAs, 7 Cs

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Aviation and the Global Atmosphere - Contents (3)

7. Aircraft Technology and its Relation to Emissions
   CLAs: Lewis (UK), Niedzwiecki (USA); 30 LAs, 11 Cs

8. Air Transport Operations and Relation to Emissions
   CLA: Bekebrede (The Netherlands); 9 LAs, 5 Cs

9. Aircraft Emissions: Current Inventories and Future Scenarios
   CLAs: Henderson (USA), Wickrama (ICAO); 12 LAs, 2 Cs

10. Regulatory and Market-Based Mitigation Measures
    CLAs: Hennigan (USA); 6 LAs

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Emissions

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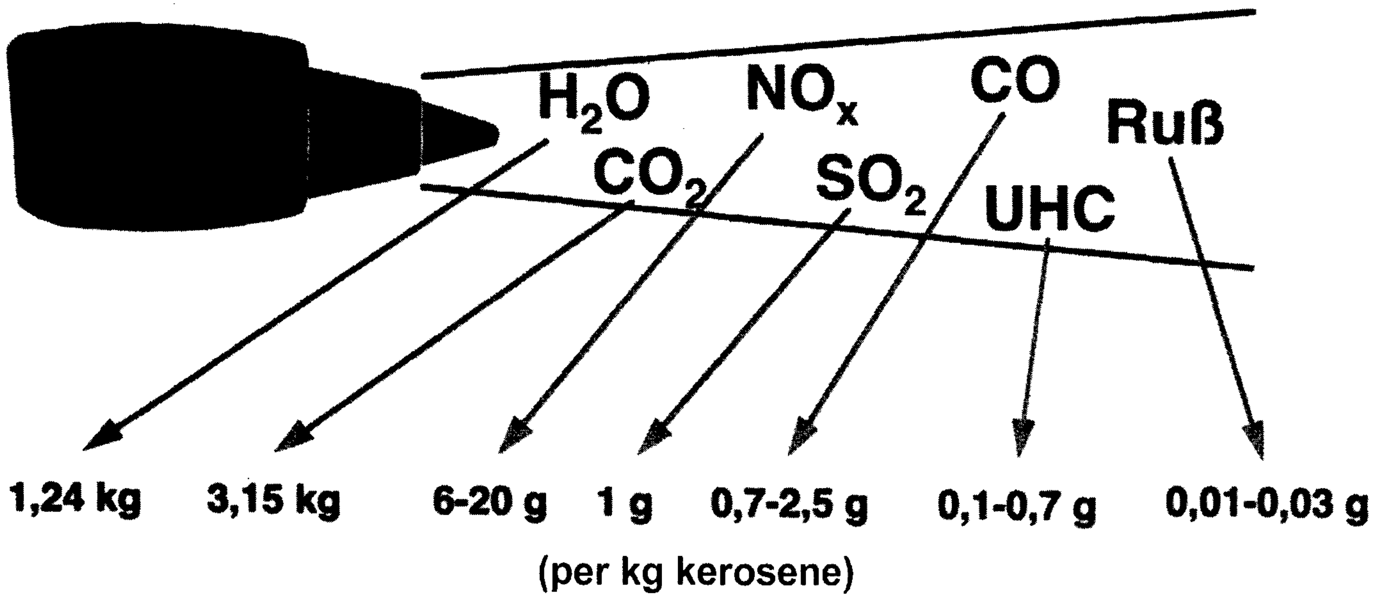
Aircraft emissions



DLR-Nachrichten 74 (Februar 1994)

Figure 8-2: Aviation share of world transport CO_2 emissions

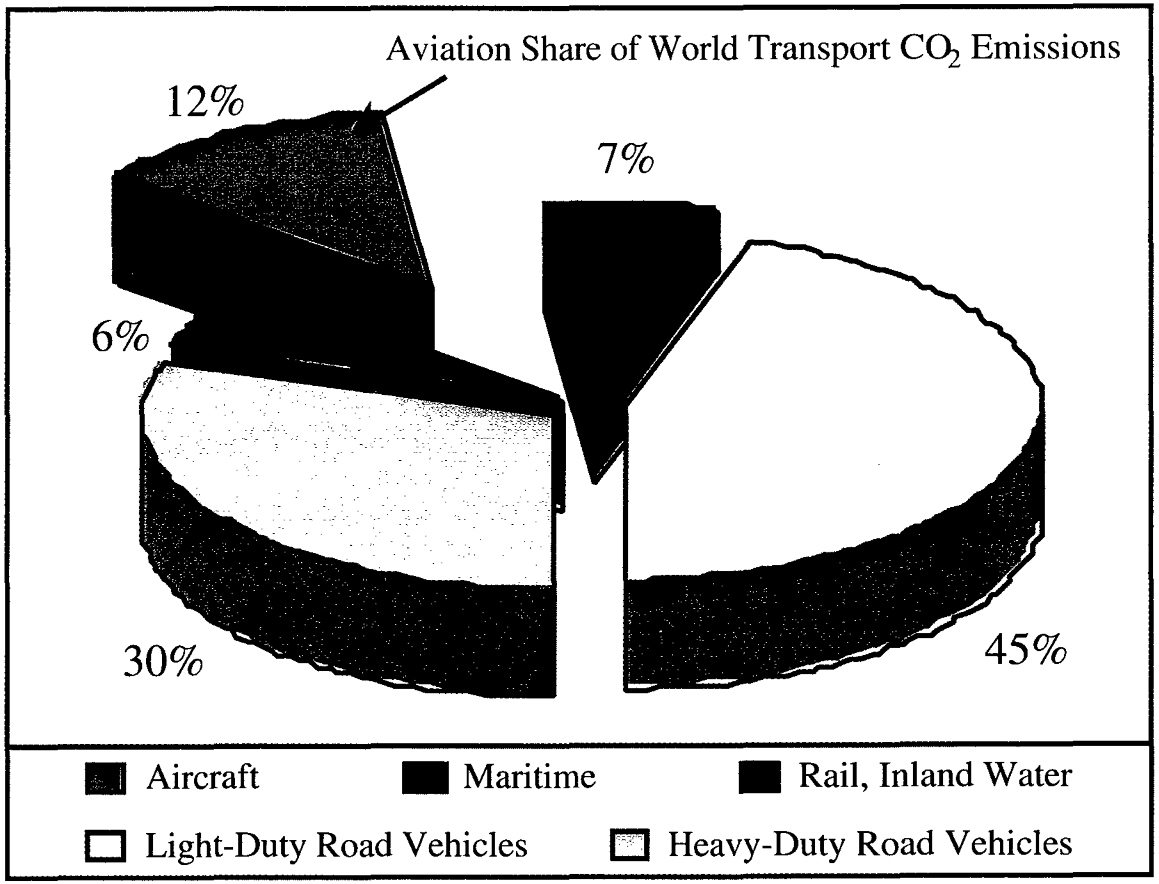


Figure 9-10: Geographical distribution of fuel burned by civil aviation (May 1992)

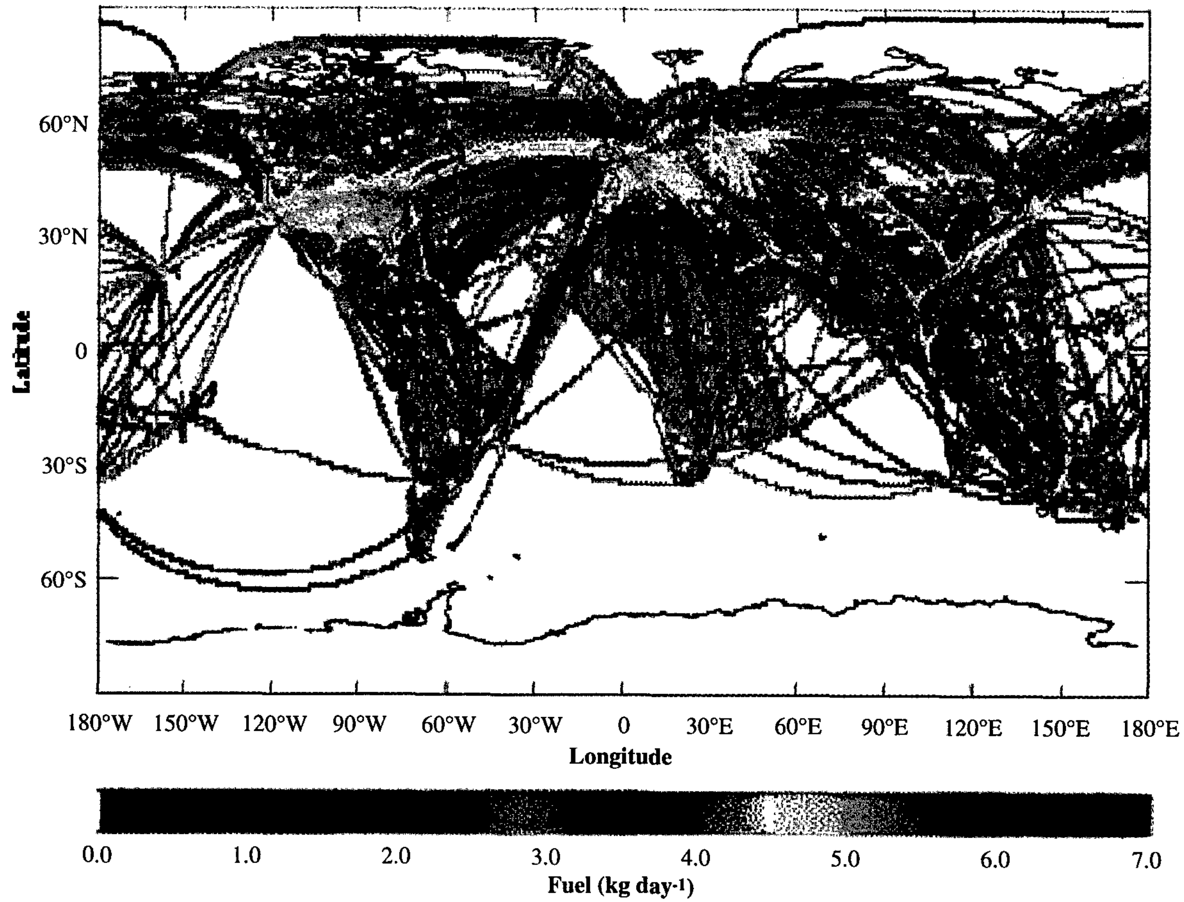
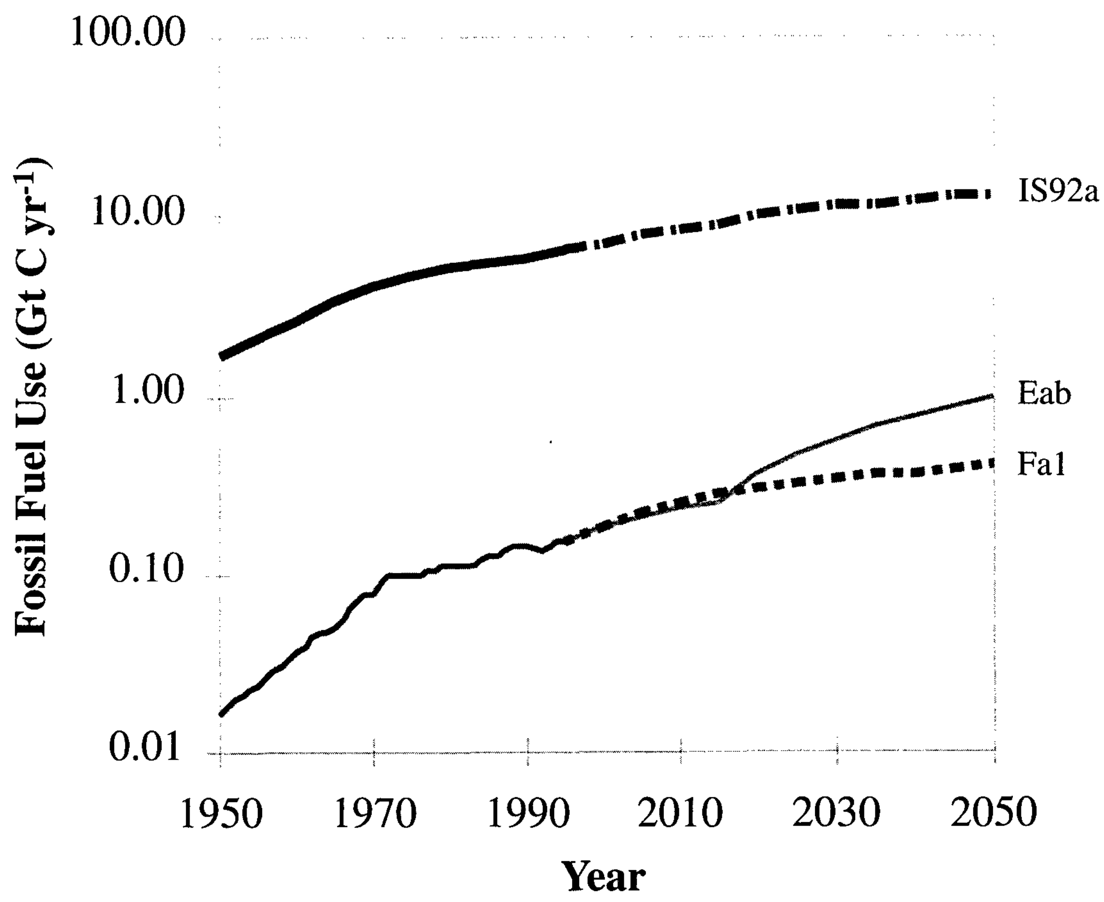
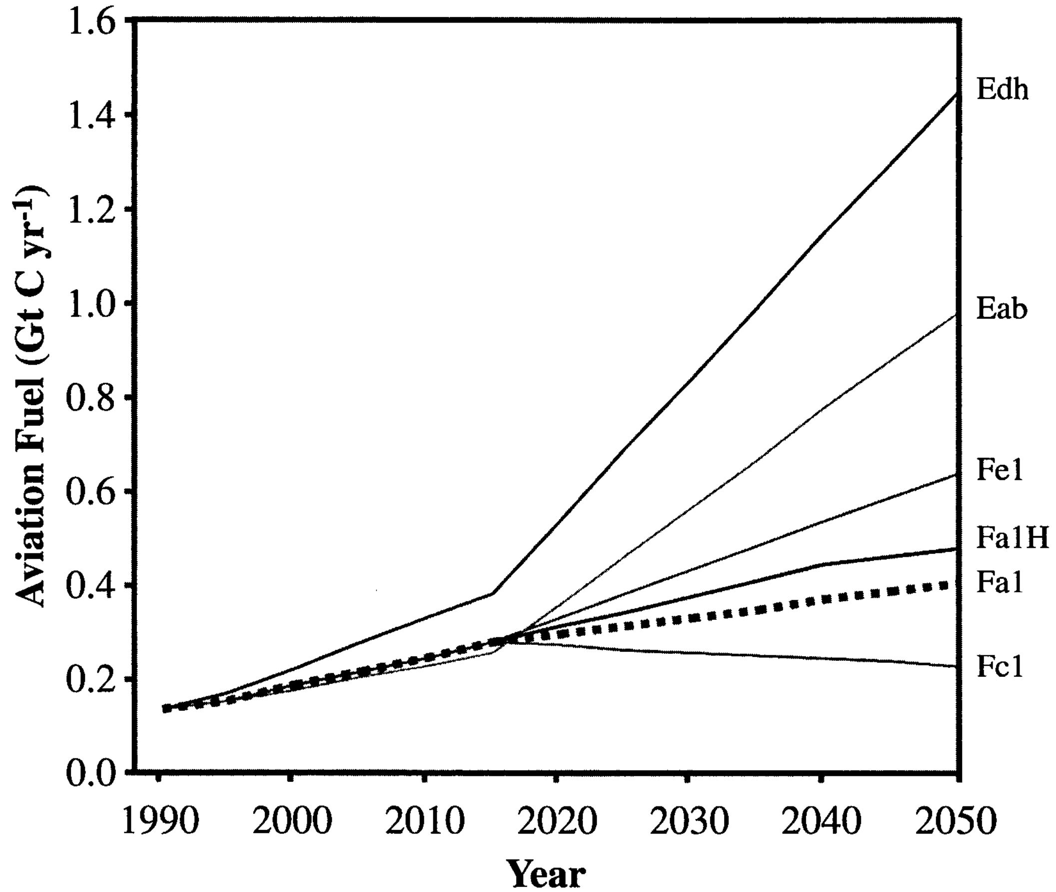


Figure 6-6: Fossil Fuel Use



Fossil fuel use (Gt C / yr) shown for historical aviation use (1950-1992, solid line) and for projected aviation scenarios Fa1 and Eab. The total historical fossil fuel use and the projection according to scenario IS92a (open circles) is also shown.

Figure 6-7: Aviation Fuel Use



Aviation fuel use (Gt C / yr) from 1990 to 2050 for the range of scenarios considered here.

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Impact on atmosphere and climate

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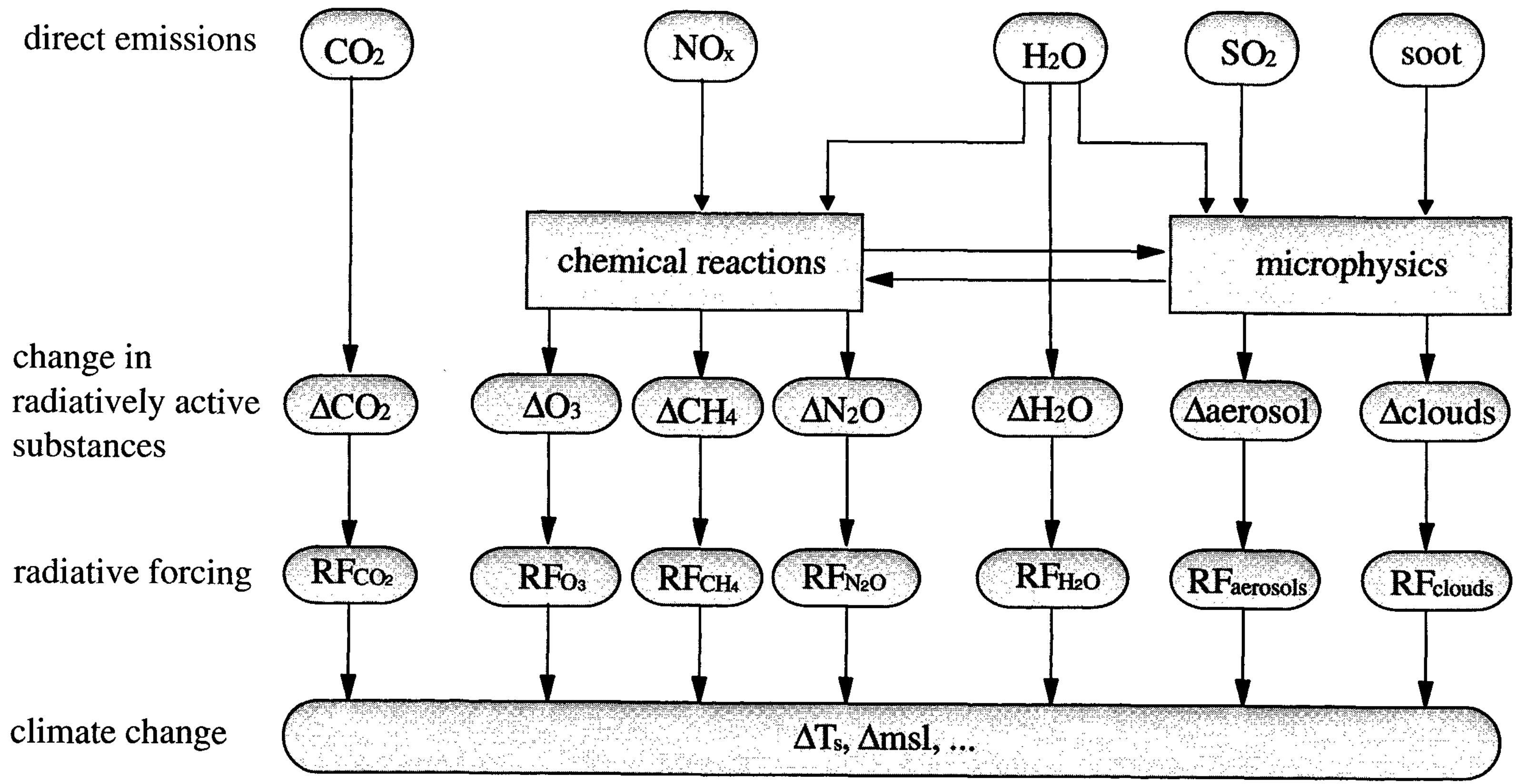
Figure 6-1: Climatic Impact of Aircraft Emissions



Schematic of the possible mechanisms whereby aircraft emissions impact climate. The climate impact is represented by changes in global mean surface temperature. (ΔT_s) and global mean sea level rise (Δmsl).

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Impact on the chemical composition of the atmosphere

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Figure 4-2: July zonal average increase in NO_x from aircraft

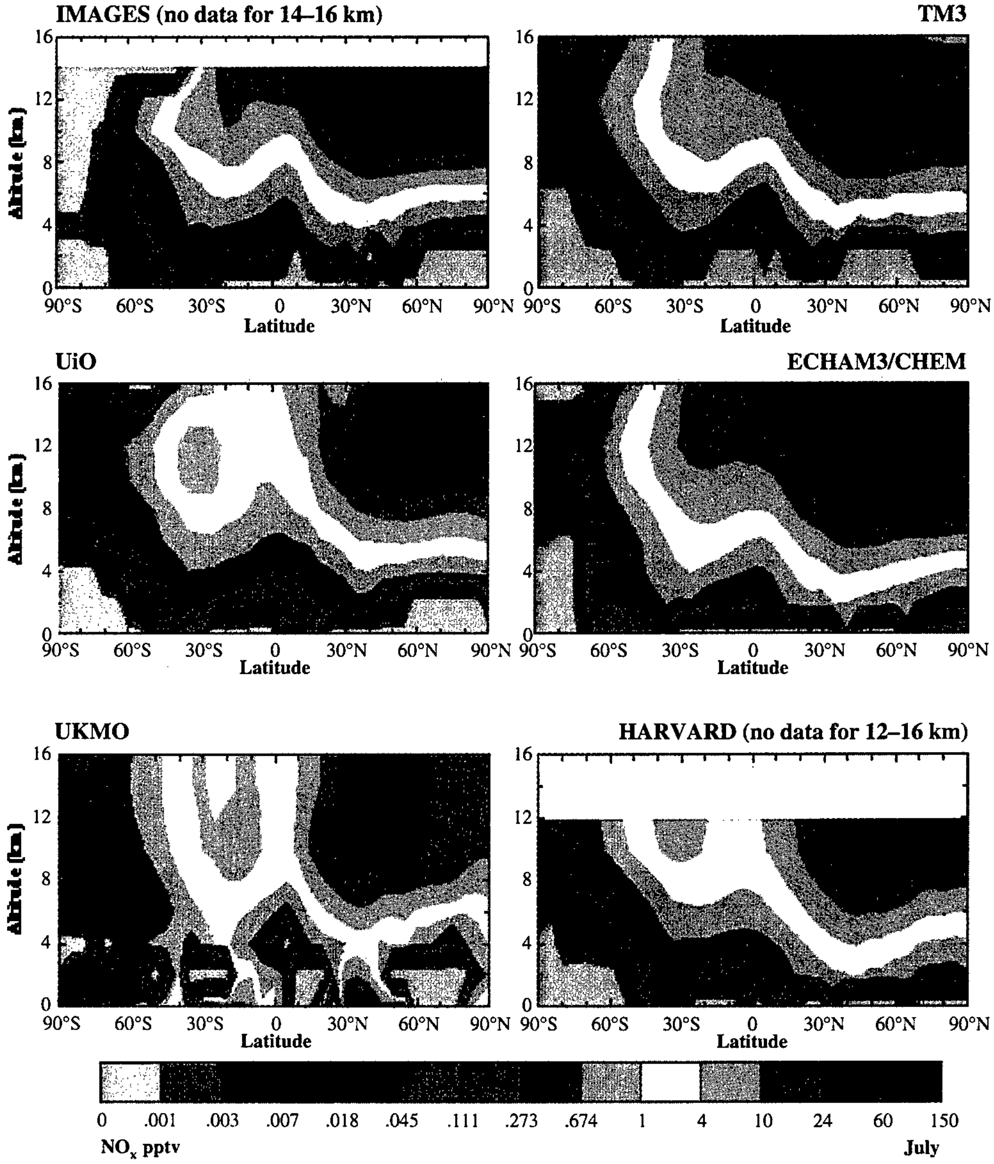
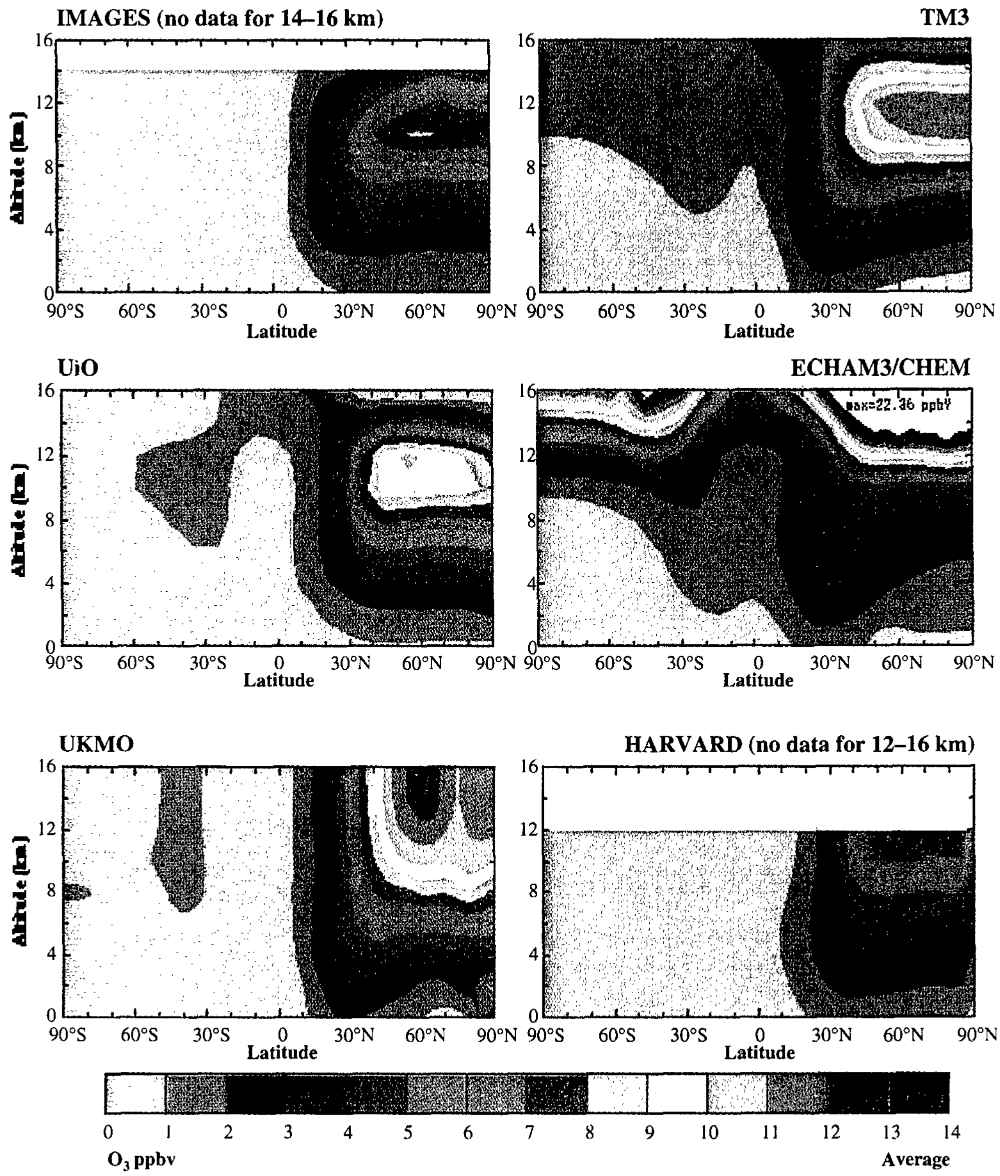
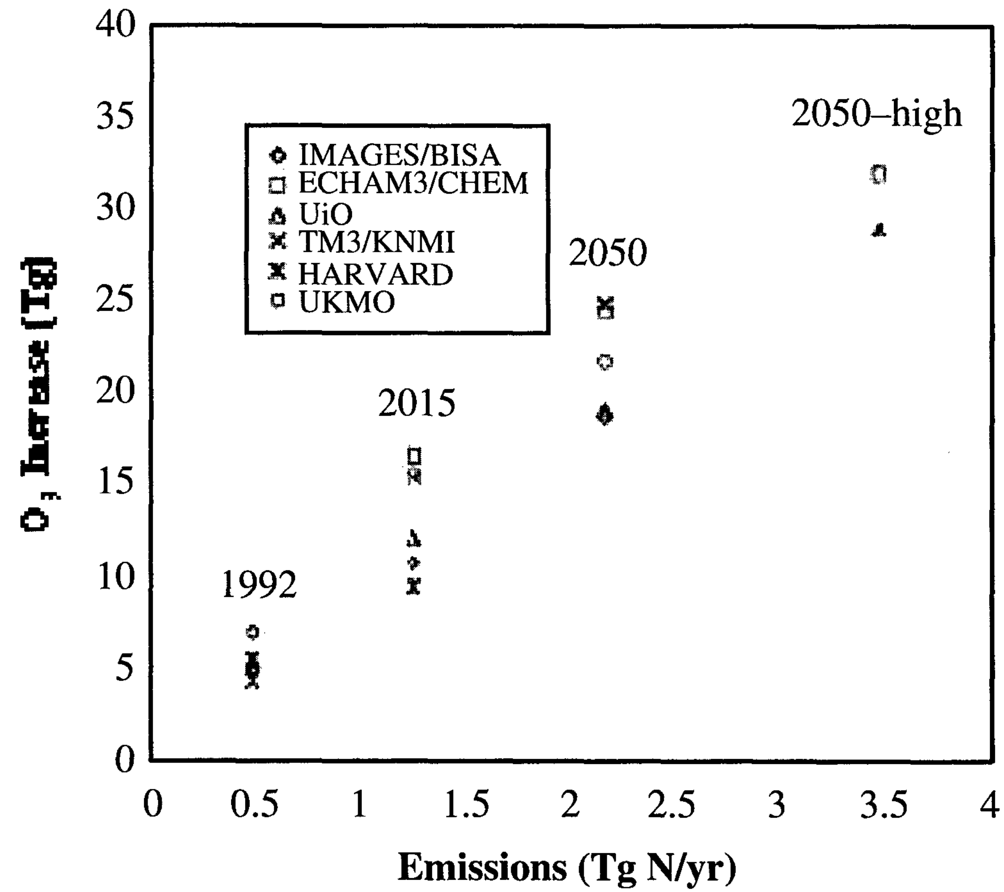


Figure 4-1: Annual and zonal average increases of O_3



Annual (2015) and zonal average increases of ozone volume mixing ratios from aircraft emissions [ppbv] calculated by six 3-D models. The IMAGES/BISAmodel does not give results above 14 km, and the HARVARD model does not give results above 12 km.

Figure 4-3: Increase in annual average global O_3 abundance



Increase in annual average global O_3 abundance (Tg O_3) up to 16 km from present and future aircraft emissions.

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Impact on clouds

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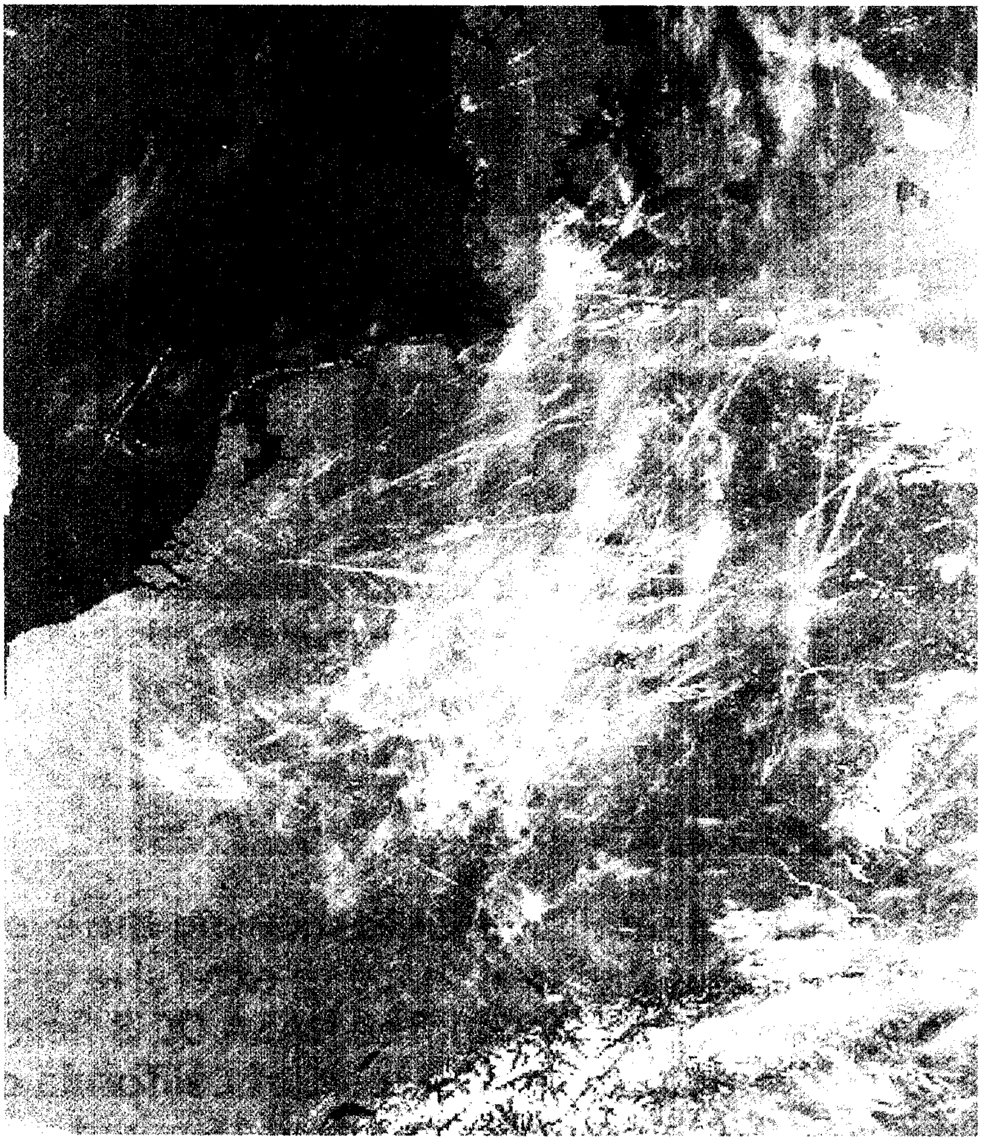
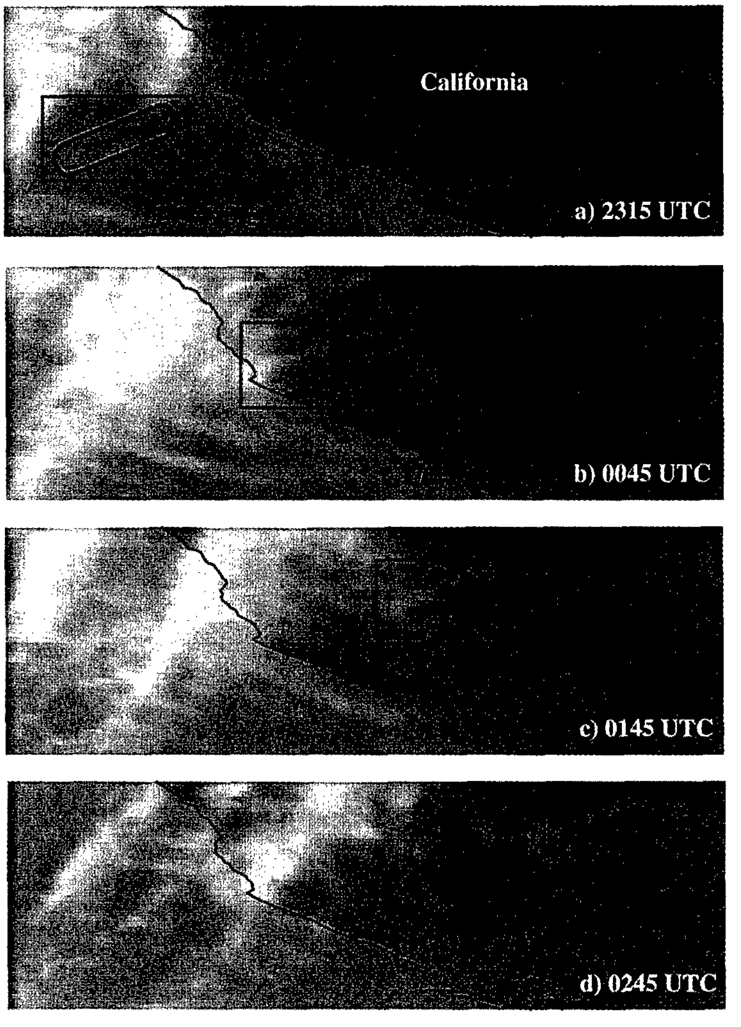
Figure 3-12: Contrails over central Europe



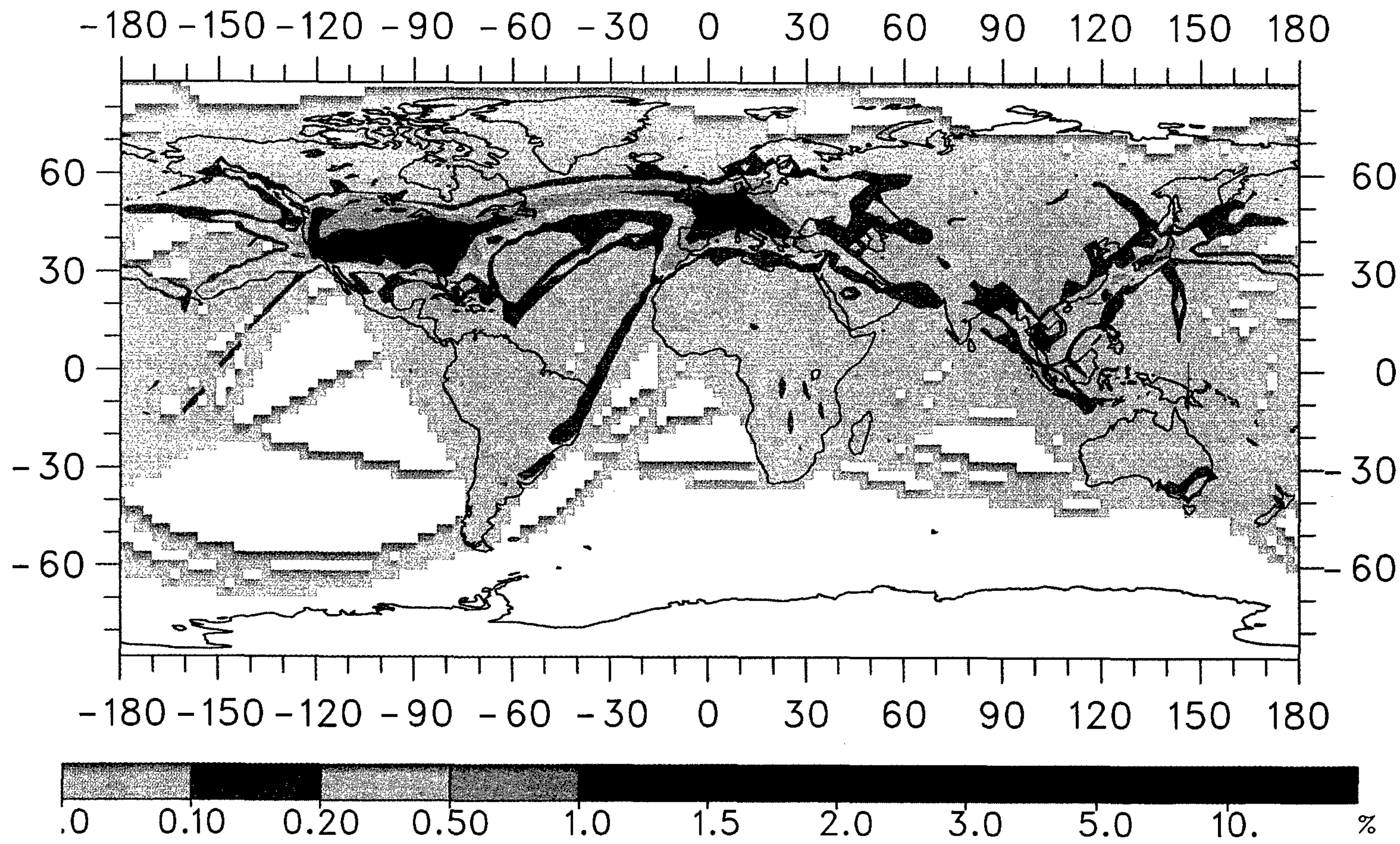
0943 UTC 4 May 1995, based on NOAA-12 AVHRR satellite data (from Mannstein, 1997)

Figure 3-13: Time series of GOES-8 satellite images

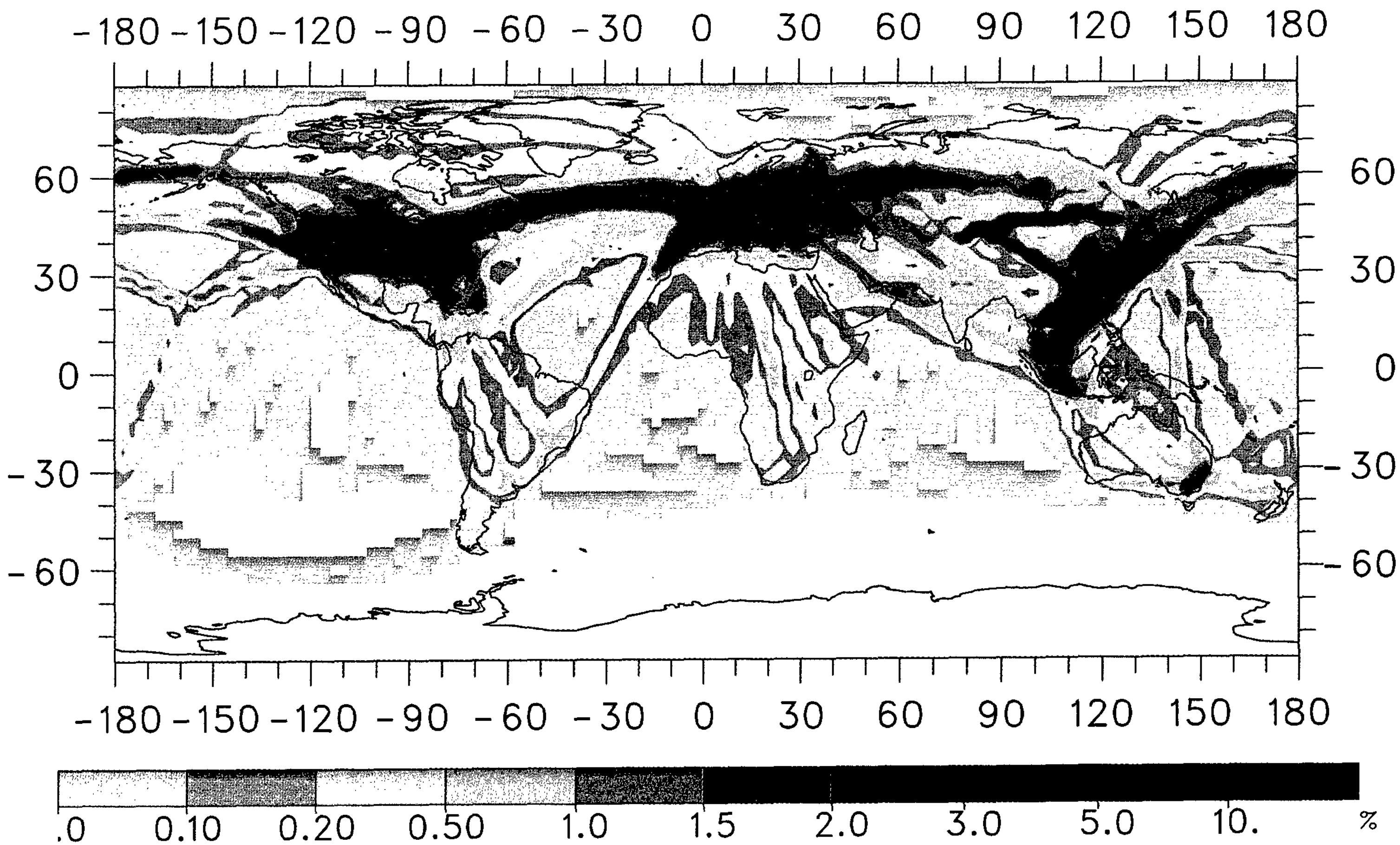


Time series of GOES-8 satellite images showing the evolution of a contrail from an initial oval shape to extensive cirrus clouds (from Minnis *et al.*, 1998a). The NASA DC-8 flew an oval flight pattern several times off the coast of California on 12 May 1996 (a), resulting in a visible contrail 15 minutes later (b). This contrail spread as it was advected over California (c), until it no longer resembled its initial shape 3 hours later (d). Satellite photographs courtesy of L. Nguyen of AS&M, Inc., Hampton, VA, USA.

Persistent contrail coverage (1992), η=0.3 linear weighting



Persistent contrail coverage (2050/1), η=0.5 linear weighting



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Impact on radiative forcing and climate

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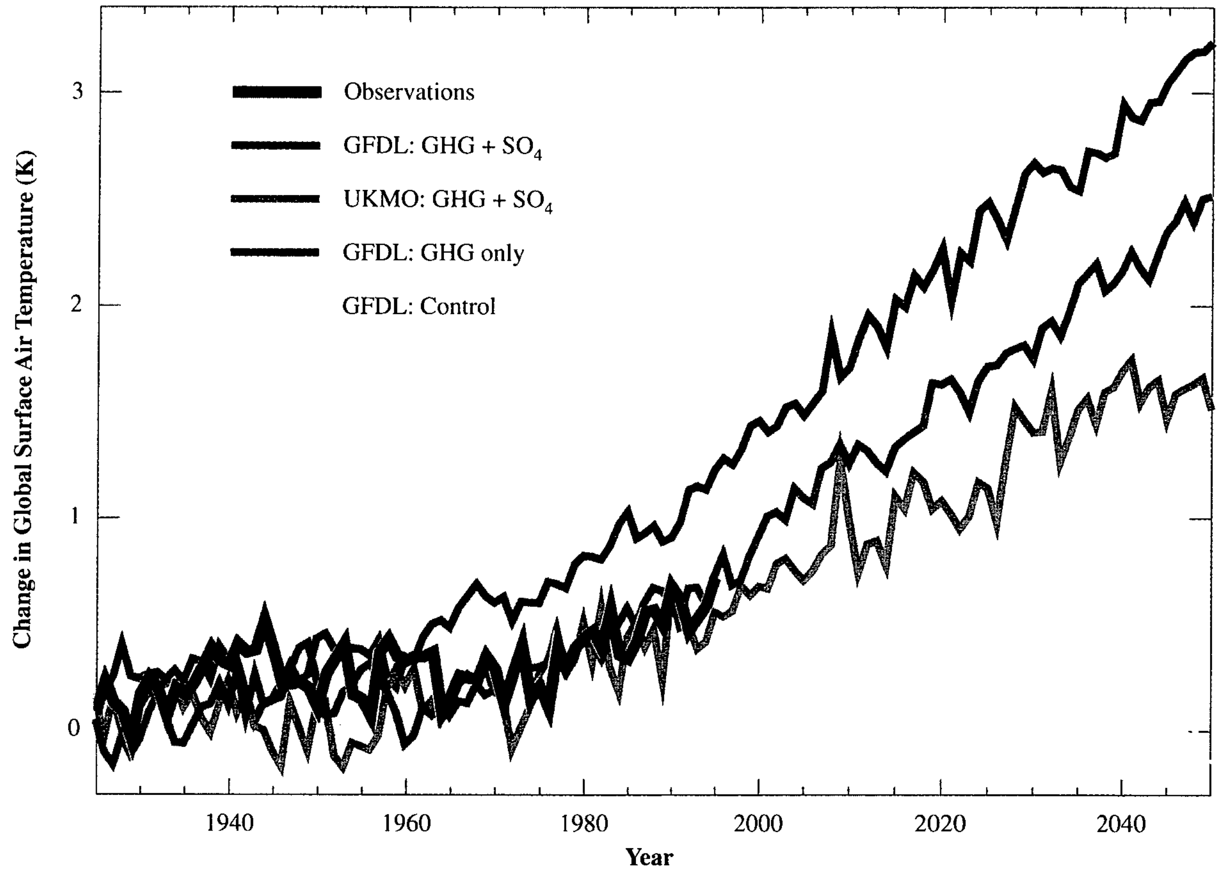
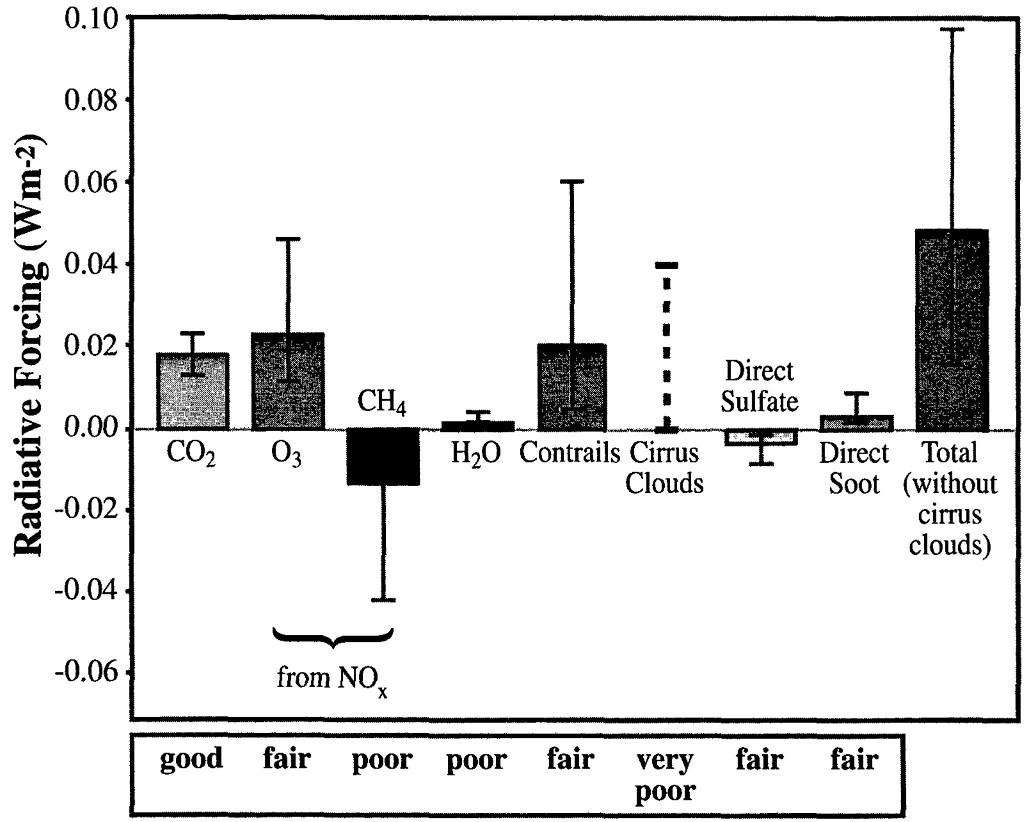
Figure 6-2: Change in Global Surface Air Temperature



The change in the global mean surface air temperature (K). Observations are from Jones (1994) modified to include data up to 1995. GFDL data are from the modeling studies of Haywood et al. (1997b) and UKMO data are from the modeling studies of Mitchell et al. (1995).

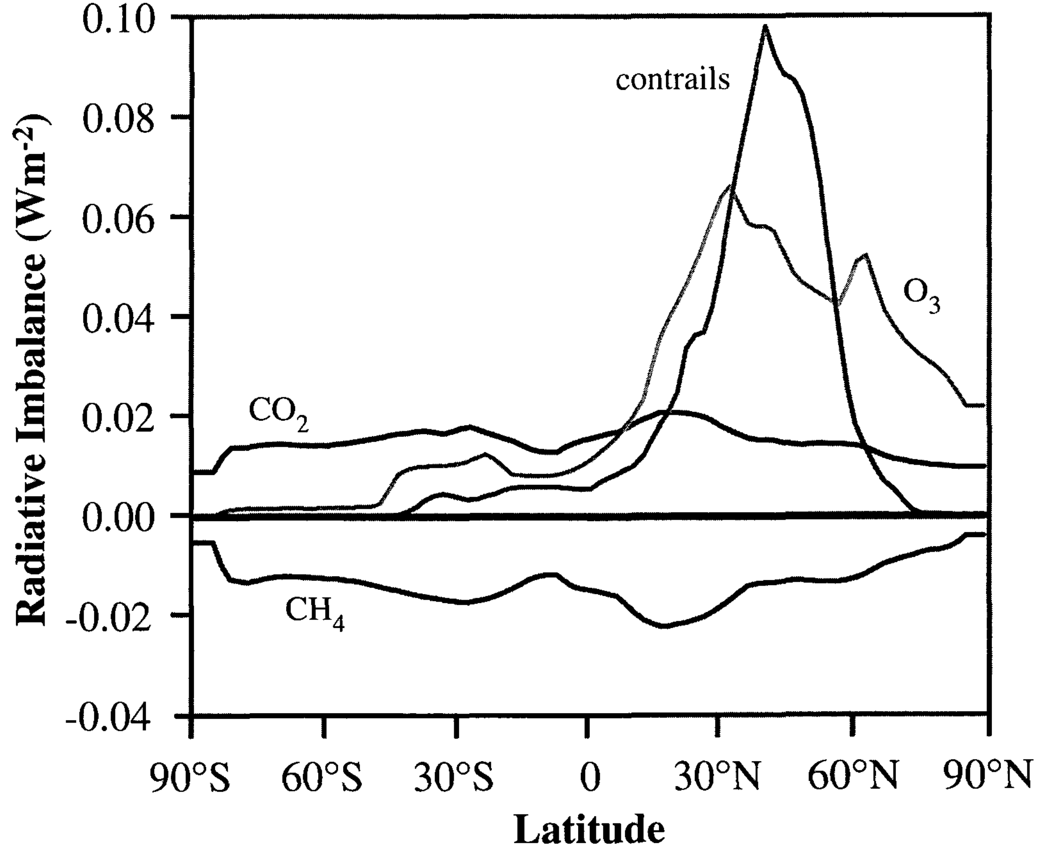
Figure 6-14b: RF (Aviation, 1992)

Radiative Forcing from Aircraft in 1992



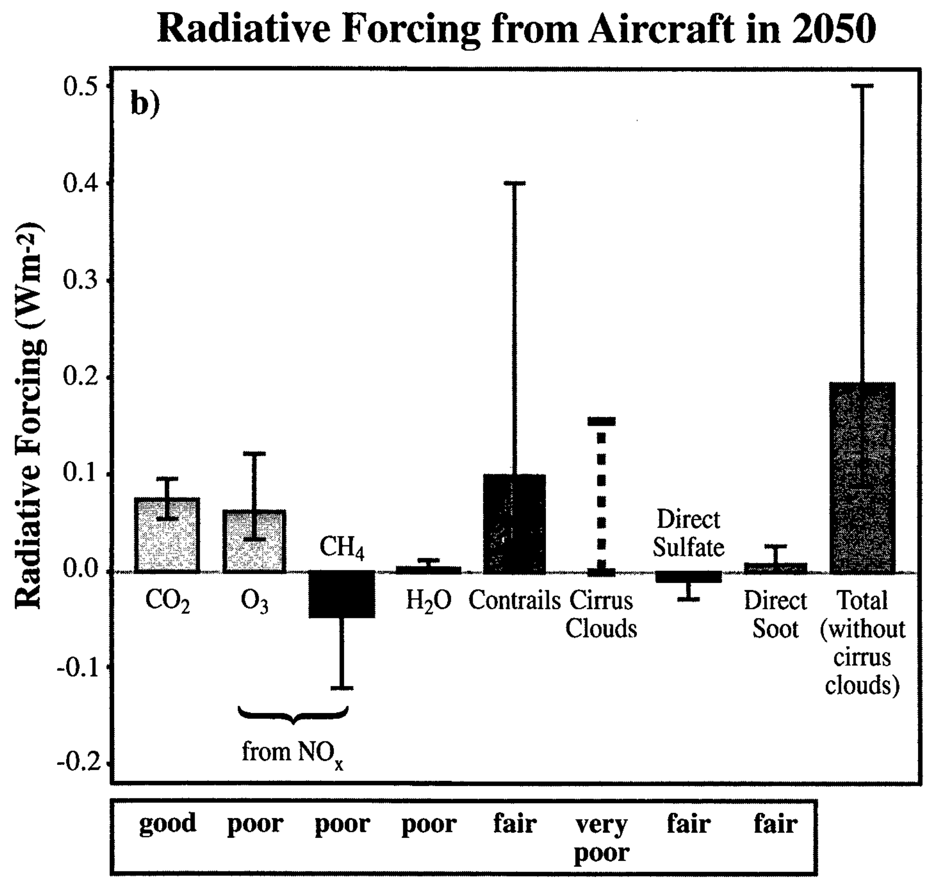
Bar charts of radiative forcing from aviation in 1992. The whiskers denote uncertainty intervals. The dashed whisker gives a range for the best estimate for Cirrus Clouds. The evaluation below the graph is a relative appraisal associated with each component and indicates the level of scientific understanding.

Figure 6-9: Radiative Imbalance at Tropopause



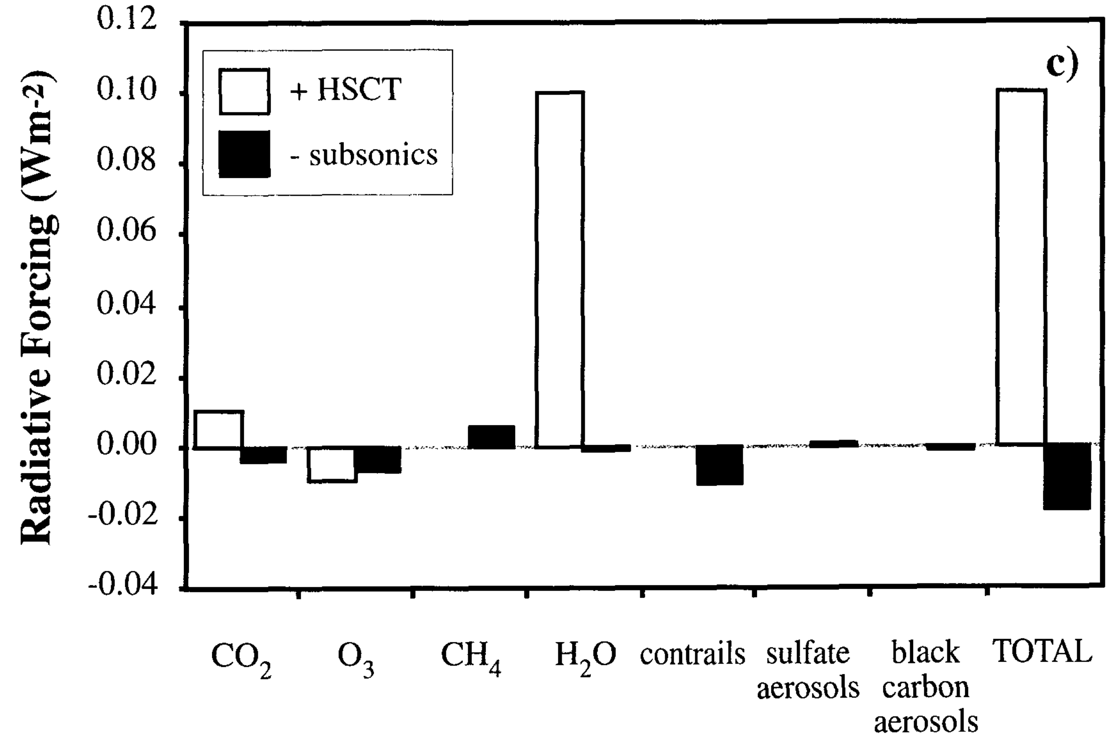
Zonal and annual mean radiative imbalance (Wm^{-2}) at the tropopause (after the adjustment of the stratospheric temperature) as function of latitude due air traffic for 1992.

Figure 6-15b: RF (Subsonic Aviation, 2050)



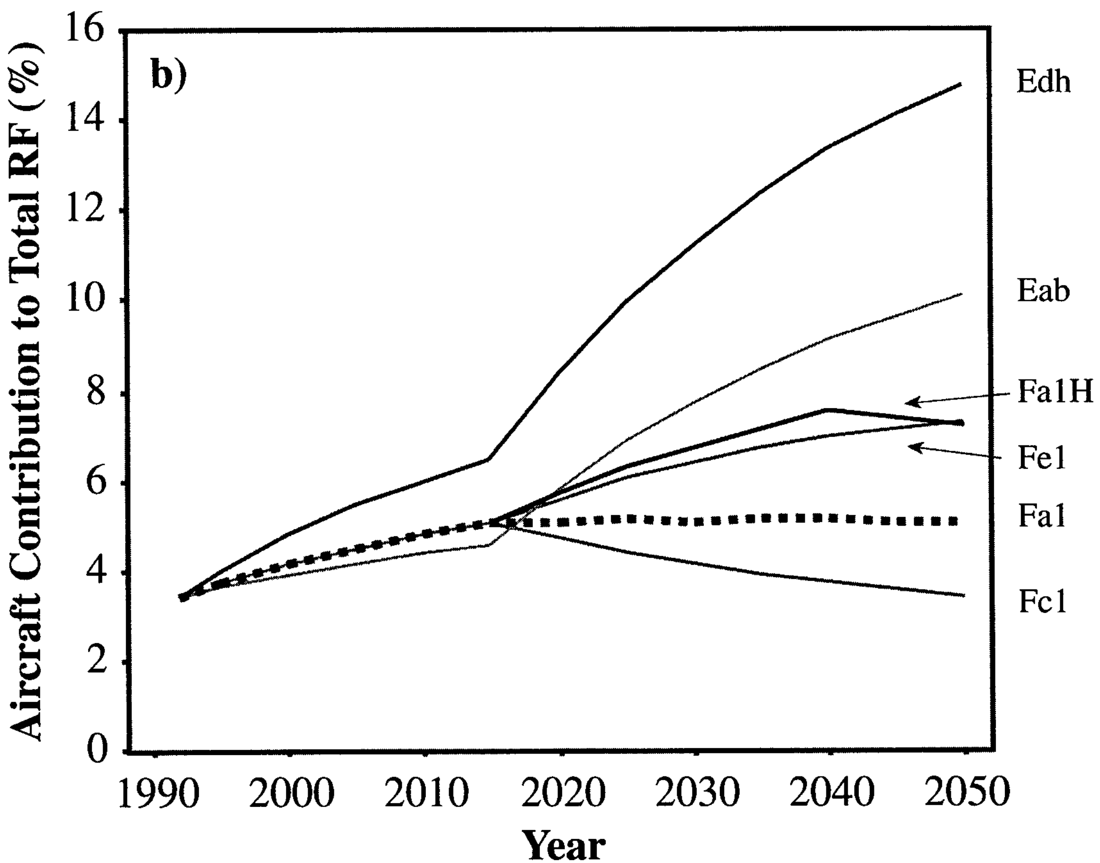
Bar charts of radiative forcing in 2050 from subsonic aviation (Fa1). The whiskers denote uncertainty intervals. The dashed whisker gives a range for the best estimate for Cirrus Clouds. The evaluation below the graph is a relative appraisal associated with each component and indicates the level of scientific understanding.

Figure 6-15c: RF (Supersonic Aviation, 2050)



Bar charts of radiative forcing in 2050 from the additional effect due to supersonic air traffic. Note scale change from (a) to (b) and (c). The white bars denote the direct effect of the supersonic fleet (HSCT1000) whereas the black bars display the change resulting from the displaced subsonic air traffic.

Figure 6-16b: Relative Aviation Radiative Forcing



Aviation radiative forcing relative to the IS92a fossil fuel use from 1990 to 2050 for the air traffic scenarios Fc1, Fa1, Fa1H, Fe1, Eab, Edh.

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Conclusions (1)

- In 1992 aircraft NO_x emissions have increased ozone concentrations at cruise altitudes in northern mid-latitudes by up to 6%.
- The ozone increase is projected to rise to about 13% by 2050 in scenario Fa1.
- The aircraft NOx emissions are expected to decrease the concentration of methane.
- In 1992, aircraft line-shaped contrails are estimated to over about 0.1% of the Earth's surface.
- The contrail cover is projected to grow to 0.5% by 2050 in scenario Fa1, at a rate which is faster than the rate of growth in aviation fuel consumption.

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Conclusions (2)

- Radiative forcing (RF) is used as metric of climate change.
- RF from CO_2, O_3 and contrails are of similar magnitude and positive, RF form CH_4 is of the same order of magnitude, but negative.
- Overall RF by aircraft is a factor of 2 to 4 larger than the RF by aircraft CO_2 alone.
- In 1992 RF by aircraft is 3.5% of the RF from all anthropogenic activity.
- In the standard scenario Fa1 RF grows by a factor of 3.8 until 2050. This corresponds to fraction of 5% of all anthropogenic RF according to IS92a.
- The RF of supersonic aircraft is larger (about 5 times) than the RF of the replaced subsonic aircraft.

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Conclusions (3)

- Additional aircraft positive RF may arise from aircraft-induced cirrus clouds.
- Some components of aircraft RF are geographically not homogeneously distributed (e.g. from O_3 and contrails), the resulting regional climate change may be larger and of different character than the global mean change

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